# ADVANCED TELEOPERATION
## Technology Innovations and Applications

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## ABSTRACT

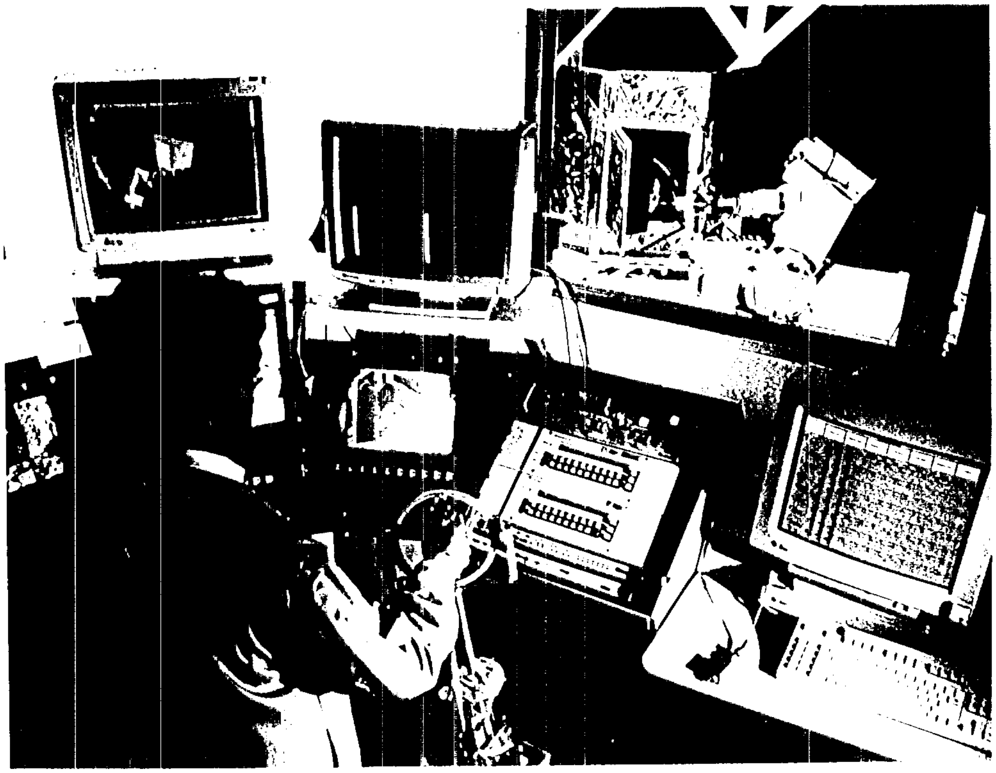
The capability to remotely and robotically perform in-space assembly, inspection, servicing, and science functions would rapidly expand our presence in space, and the. cost efficiency of being them'1 'here is thus considerable interest in developing "telerobotic" technologies, which also have comparably important terrestrial applications in areas such as health care, underwater salvage, and nuclear waste remediation. Such tasks, both space and terrestrial, require both a robot and operator interface that is highly flexible and adaptive, i.e., capable of efficiently working in changing and often casually structured environments. one, systems approach to this requirement is to augment traditional teleoperation with computer assists -- ***advanced teleoperation***. Wc have. spent a number of years pursuing this aJJpr'each, and highlight some key technology developments and their potential commercial impact below."1 "his paper is an illustrative summary rather than self-contained presentation; wc include representative technical references to our work which will allow the reader to follow up items of particular interest.

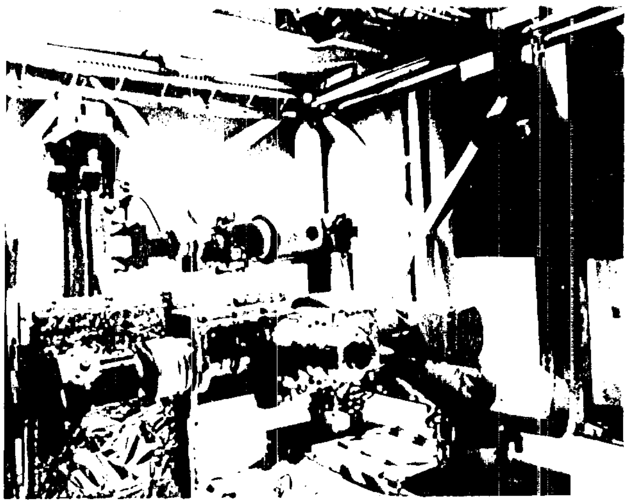
## A BRIEF TECHNICAL OVERVIEW

Telerobotics technology development [ 1 ] is motivated by a desire to remotely perform complex physical tasks uncle.r human supervisory control. To date, robotic systems that have embodied significant supervisory (autonomous) con - trol of their manipulation functions have been limited to highly structured tasks that were performed under favorable and certain conditions -- by definition not complex tasks, and not adaptive performance. T 'his has fostered the widespread use of teleoperation, which at the. other extreme from automation, is a characteristically laborious manual procedure, historically applied to hazardous environments such as nuclear materials handling, underseas recovery, and recently, space shuttle operations. *Virtual environments* and virtual reality engineering are related and currently popular areas of technology development, where.in the human operator directly manipulates or experiences a modeled, rather than physical reality, via a computer-synthesis and appropriate input/output devices (e.g., master control gloves/stcrem-in}nwrsing displays). There exists an important technical intersection of this technology with telerobotics, and specifically tele-operation: virtual environments are useful tools for simulation and design, including task analysis, training, and on-line task preview and prediction. Thus, if they can be efficiently integrated and physically calibrated with teleoperation systems, virtual environments have promise to assist the. operator's on-line perceptual, planning. rind control functions.

With regard to space applications, teleoperation systems could have important roles in remote platform servicing, telescience, and lunar exploration, as already illustrated in STS Shuttle RMS operations. However, the physical and logistical demands of space telemanipulation, particularly in less structured environments, will be high. Tasks can be physically complex and time-consuming, and the operator's manual dexterity and eye-to-hand motion calibration must be good. 1 'urther, the work will often be conducted under degraded observational conditions and thus be tedious and fatiguing. Operational uncertainties include obstructed viewing and manipulation, as well as the very disorienting effects of potential communication time-delay between the operator inputs and robot actions (a major obstacle to achieving desirable ground versus on-orbit operations). In the face of these collective problems (which have the.ir metaphors in other applications areas such as minimally invasive medical robotics and deep sea teleoperations), wc have been trying to enhance the performance of traditional teleoperation, and have made progress in the, technical areas of redundant telemanipulator control, viewing systems, real-time graJhics-based task simulation and predictive control, integrate.d operator interface design, and syskms-scale ground laboratory experiments. The laboratory photographs of the. next page give a sense of the system technology components developed, and wc comment below On specific enabling technical advances (with supporting citations). I 'or the reader seeking an engineering overview of this work, reference [2] provides a broad sampling and technically detailed survey up to 1991.

# ADVANCED TELEOPERATION TECHNOLOGY
Validation Through Simulated Satellite Repair Task





A main experimental thrust in our lab has been end-to-end systclil-level performance characterization -- formal experiment design, integrated system demonstrations, task instrumentation & data capture, and human factors analysis. Collectively, the goal has been to quantif y operator limitations, component technology requirements, and their interdependencies in the context of tasks simulated with realist ical I y posed operat ional constraints (lighting, task geometry, time-delay, control & communication bandwidths, viewing & display limitations, etc.). The accompanying technical issues are assessing technology impact on reduct ion of operator error, workload, and training, each in itself a significant risk and cost driver for space operations. As noted above, *advanced teleoperation* is computer-assisted telemanipulat ion, wherein the operator remains in manual control of the task, but with extended funct ional capabili - ties and reduced cognitive complexit y of t ask interact ion. 'J 'he computer assists we. have, developed to date encompass interactive task planning/simulation aids [3], graphics user interfaces for system programming/com mand/status display [s], and several modes of force-referenced tclcopc.rater control which arc tolerant to operator positioning error (e.g., "shared compliance control" as described in [2,7] and references therein). In its most general form, advanced teleoperation entails sensory fusion and decentralized control, given that the system sensing, planning, and control functions are inherently distributed bet ween operator and computer, and we. have developed generalized architectures and related sensory processing mode.ls and techniques in this vein 161. Regarding the controls area, wc have invest i- gated a variety of kinesthetic position, rate, force-fccdbac,k, and shared compliance modes for teleoperation [2,7]; these cont rols were first applied to dual six degree of freedom (d.o.f.) PUMA manipulators and more recently to high-dexterit y eight d.o.f. redundant manipulators [81, whose development has included computer-based techniques of task redundancy management. Wc have formall y evaluated the operat or ut i lit y of these cent rol modes, along with more traditional posit ion and rate appr oaches, through simulated space servici ng experiments [71. As one example, we performed quant ified experiments which telerobot icall y rc-enacted high dexterit y Solar Maximum M ission satellite repair procedures originally performed by astronaut extra-vehicular activity (EVA) during the 1984 space shuttle flight S'1'S- 13. Other supporting developments include real-t imc graphics environments which allow the operator to animate, analyze, and train on teleoperator tasks, and in a most gene.ral case, actually use the graphic virtual environment as a basis for reliable teleoperation under mult iplc second time delay [3,4]. Wc believe the area of graphics-augmented teleoperat ion has particular promise, for space applicat ions and comment further, by way of an example.

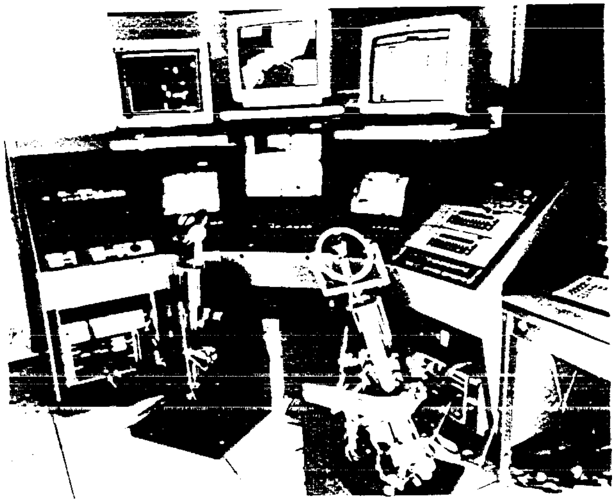
## AN APPLICATION HIGHLIGHT

A significant obstacle to the accept ance of space telerobotic systems is the. impact the.y might have on operational t imelines of crew and plat form resources. If a significant part of th is burden could be shifted to ground operat ions, them the technology benefits would be far greater, Serendipitously, utilizing ground operat ions would also free. the operator control stat ion of m an y space-borne implemen t at i on constrai nts, e.g., high degrees of compu t at ion al power could be brought to bear. The objective of ground operation of a space robot performing a complex task confronts a basic system limitation: robotic automation is not yet sufficiently generalized to allow control by uplink sequencing of d iscrete high-level commands. Rather, the operator's cont inuous direct manual control and eye-to-hand perceptual coordination is required. However, the implied ground-to- orbit teleoperat ion approach will not suffice either. The problem lies in t ime-delay communicat ions transit (2- 10 seconds latency in current scenarios). The oJw.rater cannot "fly-by-wire" confidently or coordinate his eye-to-hand skills when causal action-reaction is on the order of seconds; in fact, people rapid l y adopt a move-and-wait behavioral pat tern when latencies are greater than .2.5 seconds.

Our approach to resolving this fundamental limitation is to develop a class of 3-D graphics display which visually simulates the robot response in real-time immed iacy to the operator's input. in essence, the operator interacts with a virtual task model. 'J'bus, the critical details of the task (and robot itself) must be accurately niodc.led, and further, must be very accu ratel y geomet ricall y calibrated to the operator's real (t ime-delayed) video percept ion. In terms of practical implementation, this results in a 3-D high-fidelity graphics display which must be correctly registered in t ranslat ion, scale, and aspect to the mult icamera video display. See the second page of laboratory photographs for a represent at ive example. Our development of this *predictive graphics display* (with a cal ibrated virtual realit y) has enabled us to preserve the operational feat ures of teleoperat ion, and operate with interm it tent time dcla ys up to 5-10 seconds. in a recent demonstration depicted in the lab photos, we, in coordination with colleagues at NASA Goddard Space Flight Center, performed a simulated on-orbit equipment changeout function similar to that anticipated for future Hubble Space Telescope servicing: from JPL, having, modeled and calibrated the remote GSFC robot site., wc teleoperativel y detached and remounted an ORU. The motion planning and execut ion, both in free space and guarded-contact, were generated by teleoperation, with accuracies of mill imeters over a work volume of meters[3].

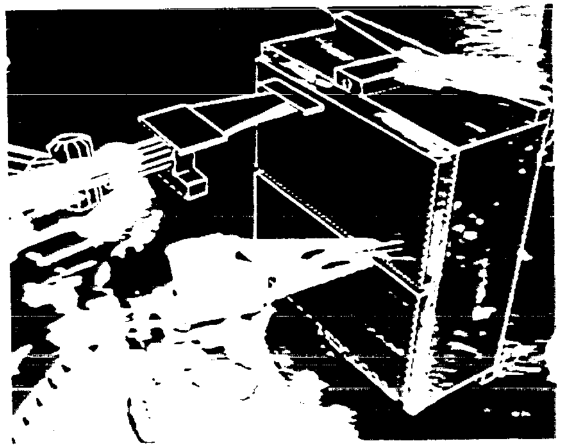
# ADVANCED TELEOPERATION WORKSTATION

**Dual-Arm Control with Graphics Displays**
for Task Preview and Time-Delayed Operations

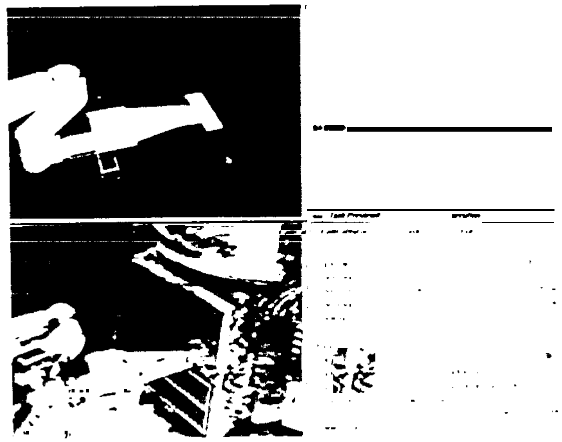


# CALIBRATED VIRTUAL ENVIRONMENT FOR ADVANCED TELEOPERATION

JPL-to-GSFC Time-Delay Operations
for Simulated HST Platform Repair



(time delay remote video with calibrated 3-D graphics overlay)



(robot operator's multi-media display during task)

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## COMMI ;RCIAI , MARKI ;TS

The ability to calibrate and animate a virtual environment with respect to actual visual robotic workspaces appears to have significant applications potential. As onc example, in the area of medical robot ics, it suggests a number of possi - bilities for computer-guided stereotaxic procedures, microtelerobotic surgery, telesurgery proper (actual remote surgi- cal theatres), also multisensory data presentation and visualization. And of come, calibrated VR seemingly is a key ingredient in planning and execut ing telerobot ic operations in remote scenarios subject to either t imc delay red/or partial viewing obstruction. To this end we have joined with Deneb Robotics, inc., of Auburn Hills, Ml, to coopera- tively develop a calibrated 3-D graphics-on-video function within their line of 3-D graphics simulation products.

## ACKNOWI ;EDGEMENTS

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simulated ground-to-remote on-orbit equipment changeout similar to that anticipated for future Hubble Space Telescope servicing: from JPL, having geometrically modeled and visually calibrated the "remote" GSFC robot site, we teleoperatively detached and remounted an ORU. The motion planning and execution, both in free space and guarded-contact, were generated by pure teleoperation, with accuracies of millimeters over a work volume of several meters cubed.

## COMMERCIAL MARKETS

The ability to calibrate and animate a virtual environment with respect to actual visual robotic workspaces appears to have significant applications potential. As one example, in the area of medical robotics, it suggests a number of possibilities for computer-guided stereotaxic procedures, microtelerobotic surgery, telesurgery proper (actual remote surgical theatres), also multisensory data presentation and visualization. And of course, calibrated VR seemingly is a key ingredient in planning and executing telerobotic operations in remote scenarios subject to either time delay and or partial viewing obstruction. To this end we have joined with Deneb Robotics, Inc., of Auburn Hills, MI, to cooperatively develop a calibrated 3-D graphics-on-video function within their line of 3-D graphics simulation products.

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